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REVIEW

The Essential Role of the Lagg in Raised Bog Function and Restoration: A Review

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Abstract The lagg of a raised bog is a transition zone where runoff collects from the ombrotrophic (rain-fed) bog and adjacent mineral soils. Distinct hydrological and hydrochemical gradients exist across the lagg zone, resulting in specific plant communities. Little research emphasis has been placed on the lagg zone in the past, with studies tending to focus on the more easily-defined bog instead. Recently, peatland researchers have begun to discuss the importance of the lagg to raised bog restoration. This paper reviews current knowledge on lagg zones, the function of this transition zone, some useful indicators to determine its location in the field, and argues that restoration of the lagg should be a key element in raised bog restoration.

Keyword Ecotone

Introduction

Lagg is a term in peatland ecology that refers to the transition zone between an ombrotrophic bog and the mineral soils of the surrounding landscape. Osvald (1933) was one of the first authors to recommend the use of the Swedish term "lagg" in the English literature, and defined lagg as the wet margin around a raised bog. Rigg (1925) and Rigg and Richardson (1938) used the term "marginal ditch," when referring to swamps and thickets found at the borders of the North American bogs they studied. Millington (1954) makes reference to a "lagg stream" drainage feature in Australian bogs, noting that the vegetation changes sharply on either side of the lagg. Damman and French (1987) define lagg as "the nutrient-enriched zone at the margin of a raised bog, receiving water from the surrounding mineral ground and from the bog itself." The lagg is often referred to as minerotrophic and is generally described as containing fen vegetation (Damman and French 1987; Rydin et al. 1999), although Rydin and Jeglum (2006) expand the definition to include swamp vegetation.

The lagg and rand are both elements of the raised bog margin. The rand is defined as the outward-sloping margin of a raised bog (Wheeler and Shaw 1995) situated between the bog and the lagg. The lagg is most strongly developed in bogs with steep rand slopes and abundant runoff. Bogs with a low summer moisture surplus and flatter rand produce a less clearly-defined lagg zone (Damman 1979). Wheeler et al. (1995) note that smaller bogs generally lack the characteristic elements of a raised bog, such as hummock-hollow or pool-string systems, lagg, rand, and central plateau, suggesting that only large mires produce the complete raised bog complex. Raised bogs that are physically constrained by basins often develop a "moat-like" lagg, where waters from the bog and surrounding upland converge and cannot easily escape from the topographic depression. A more diffuse lagg may form if the bog grows beyond the confines of the basin or if the surrounding landscape is relatively flat. Where rivers or streams converge with a raised bog, an entirely different form of "riparian" lagg develops in which the transition zone can be relatively abrupt and may be influenced by occasional flooding. Many of these different lagg forms have been described in reference to Burns Bog, a raised bog in western Canada, by Howie et al. (2009a).

The lagg zone may be lacking from some areas of the bog margin, be barely discernible, or not present as a

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distinct feature at all. This may occur in cases where the transition from bog to mineral soil is very gradual (Damman 1977) or where the raised bog merges with a blanket bog or bog forest (Banner et al. 1986). Gorham (1950) conducted a detailed study of a "fen lagg" of a Swedish raised bog and found that the lagg was "clearly developed" in one quadrant of the mire whereas lagg development was "negligible" at other locations around the margin. Eurola (1962) and Aartolahti (1965) (as cited in Lindholm and Heikkilä (2006) and Laitenen et al. (2007)) both observed that a significant number of Finnish raised bogs do not contain laggs.

In order to describe this landscape feature in terms of the latest understanding of its form and function, we propose the following expanded definition for lagg based on the above definitions and the additional details presented in this paper:

> "Lagg: a transition zone at the margin of a (usually raised) bog receiving water from both the bog and surrounding mineral ground, characterized by fen or swamp vegetation, transitional water chemistry, and shallow peat of relatively low hydraulic conductivity; the lagg transition may be sharp or diffuse (depending on the topography), or may not be present as a distinct feature."

We recommend using the general term "margin" to encompass both the rand and lagg transitional elements, or to refer simply to the bog border where these elements are not distinguishable, and using "lagg" specifically for the transition zone that develops where ombrotrophic bog waters mix with minerotrophic runoff. Figure 1 summarizes the role of the lagg in graphical form. The dotted line represents the boundary between acrotelm and catotelm, or the average low point of the water table. The water table drops in the rand, allowing increased tree growth at the margin of the bog. Water collects between the bog and upland, promoting the growth of sedges and other fen vegetation. In contrast, the runoff in the gradual lagg transition diffuses over the surface, allowing larger shrubs and trees to establish. The bog water also spreads further in the flat lagg transition, particularly in winter, which strongly influences species composition at the bog margin. Calcium concentration and pH increase from bog to mineral soil. Hydraulic conductivity (K) is highly variable in the bog and often lower in the denser peat of the lagg. Each of these aspects is described in detail in this paper.

A lagg is an ecotone: a transition or tension zone between two adjacent plant communities evidenced by a relatively sharp change in plant species composition in space (Gosz and Sharpe 1989; Groenveld and Or 1994; Kent et al. 1997). An ecotone is dynamic, responding to fluctuations in environmental constraints, and can be a sensitive indicator of changes in influencing abiotic factors (Gosz and Sharpe 1989) and the interactions with adjacent plant communities (Groenveld and Or 1994). Since sharp changes in hydrology, chemistry, and species composition may occur across an ecotone (Gosz 1992), these landscape forms are often high in biological diversity and productivity (Risser 1995). The diverse species composition of lagg zones may thus be an important element in regional biodiversity.

Much research has focused on the abiotic/biotic characteristics and processes, history, development, and restoration of bogs. The majority of these studies have focused on the central bog expanse, with little discussion about the lagg transitional zone. The exception is the literature related to the development and structure of raised bogs (e.g., Ivanov 1981; Ingram 1982, 1983; Hobbs 1986; Damman and French 1987). The classic model of raised bog formation often describes a wetland system passing through lacustrine and fen stages before peat accumulates to the point that part of the surface becomes ombrotrophic and drains towards a remnant marginal lagg fen (Ivanov 1981; Svensson 1988). McNamara et al. (1992) further expand upon the concepts of Ivanov (1981) and Ingram (1982) to suggest that differential accumulation of peat in some fens results in the formation of ombrotrophic conditions, whereby peat accumulation is supported both by impeded drainage and the presence of springs at the bog margins. Thus, where a lagg fen is present at the margin of a newly forming bog, the lagg may enhance peat accumulation and water mound formation due to low hydraulic conductivity of lagg peat and a water table supported by minerotrophic streams or springs in the lagg (McNamara et al. 1992).

Several studies have investigated the poor-rich gradient in peatlands, whether between separate fen and bog sites (Glaser 1992; de Mars and Wassen 1999; Tahvanainen et al. 2002; Hájková and Hájek 2004) or along the "mire margin–mire expanse" gradient within a particular bog landscape unit (e.g., Sjörs 1950; Malmer 1986; Bragazza et al. 2005; Sottocornola et al. 2009). Most commonly, these studies attempt to isolate the key influences on plant species composition, such as depth to water table, acidity-alkalinity, and fertility (Bragazza et al. 2005). Field researchers examining the transition from bog center to margin rarely extend beyond the mire margin into the surrounding minerotrophic ecosystem (e.g., forest), and therefore tend to ignore the variable chemical composition of runoff from the adjacent landscape.

Only a few studies specifically looked at the lagg zone. Blackwell (1992) explored the sources of water to the lagg zone of an Irish bog and developed a two-dimensional model of flow into the lagg. Similarly, Smit et al. (1999) focused on the hydrological conditions of a lagg in

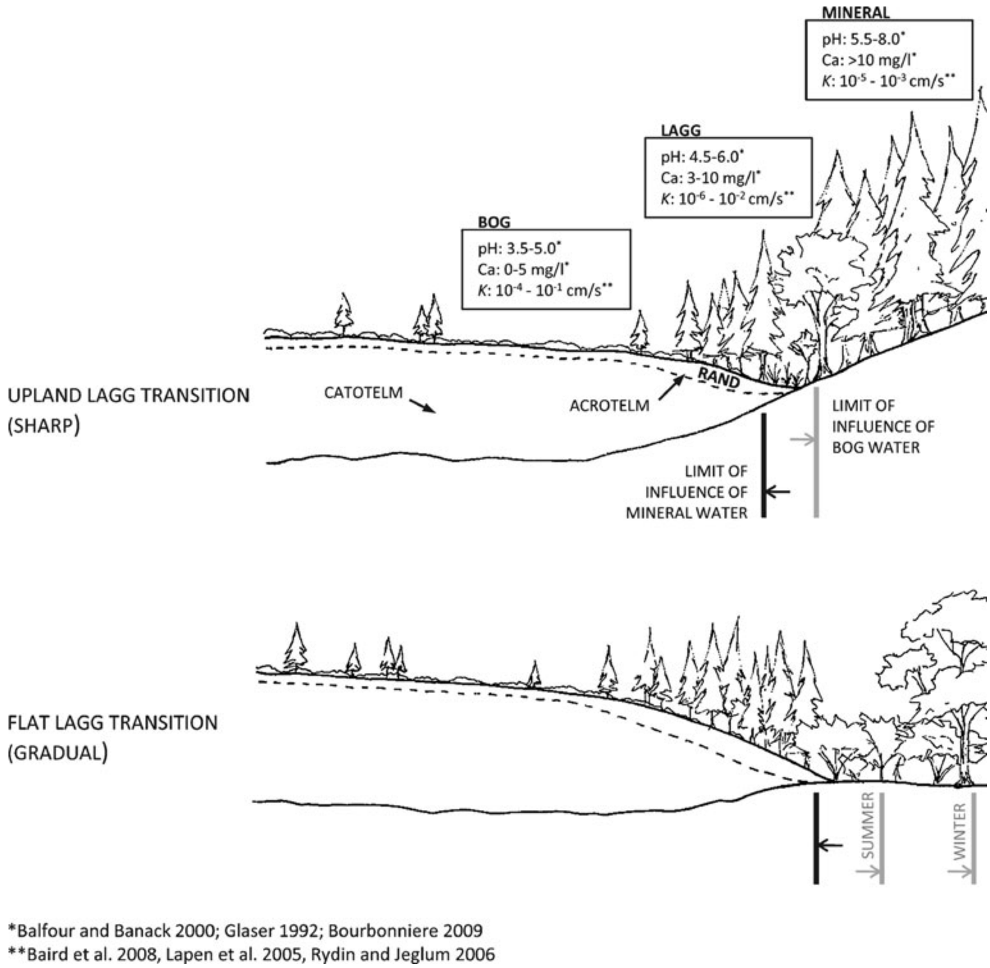

Fig. 1 Cross section of two lagg forms (upland and flat), with associated hydrological, hydrochemical, and vegetative characteristics of each. Calcium, pH, and hydraulic conductivity values are compiled from numerous studies for illustrative purposes; actual values will vary by region

Scotland. Peregon et al. (2009) looked at the historic rate of lateral expansion of two Siberian raised bogs, which included characterizing the vegetation and geomorphology of the lagg zone. As illustrated in these examples, where research has been conducted in the lagg zone, the goal is rarely to develop a holistic understanding of the lagg zone itself or its relation to adjacent lands; rather, the lagg tends to be a venue for research on specific elements of this transitional zone, such as hydrology, hydrochemistry, or vegetation.

Marginal zones, such as the lagg, tend to be disturbed first due to agriculture or other development, and are frequently disturbed even for bogs that are in a (near) natural condition in their central parts. In studies related to restoration of raised bogs, there has been surprisingly little emphasis on restoration of the lagg system in conjunction with restoration of the associated raised bog. Hughes and Barber (2003) note that the "fen-bog transition" has received little research emphasis, and suggest that it is necessary to understand the mechanisms involved in this transition zone with respect to raised bog management and restoration. Holden (2005) similarly comments that researchers have only begun to think about integrating the area outside the bog in terms of hydrological management, while most restoration efforts continue to focus on the bog itself or just the area within the bog that has been set aside for conservation. Whitfield et al. (2009) recommend further research in the form of hydrological and hydrochemical transects across the transition zones between minerotrophic and ombrotrophic sites, and note that the "role of the lagg as a transition and as a boundary needs to be better understood and modeled." In this paper, we review the form and function of the lagg transition zone, some useful lagg indicators, and argue that restoration of the lagg is a critical element in raised bog restoration.

Lagg Formation and Hydrology

As an ombrotrophic peatland develops, rising above the surrounding water table and spreading outwards, the minerotrophic (lagg) vegetation usually becomes marginal and a small stream develops at the bog border (Godwin and Conway 1939). The lagg stream shifts outward to accommodate the outward spread of the bog, but as a lagg stream deepens and the flow rate increases, the lagg may eventually become so deep and mineral-rich that *Sphagnum* growth will be inhibited and the lateral spread of the bog cannot continue (Godwin and Conway 1939; Ingram 1983). The water table of a raised bog can become elevated several meters above the water table in the lagg. Depth to water table is typically smallest in the bog center and increases towards the lagg, at which point the water table may reach the surface again as flow is impeded by topography or other physical barriers (Damman 1986).

Ombrotrophic bogs are often described as being separate from the regional groundwater system; ombrotrophic literally means "rain-fed." However, Glaser et al. (1997) presented evidence that raised bogs in northwestern Minnesota are buffered from changes in climatic conditions by groundwater recharge, suggesting that these bogs are not maintained by precipitation alone. Ground water was found to move upwards into the water mounds of these raised bogs during drought conditions, whereas during wet periods the infiltrating water pushed the upwelling ground water down and away from the bogs (Glaser et al. 1997). Since groundwater upwelling only occurred periodically and on a short-term basis, the pore-water chemistry and plant communities did not appear to be affected by this upwelling. McNamara et al. (1992) found similar evidence of upwelling, and suggested that the bog surface was not affected due to very slow movement of solutes through the peat. This groundwater influence could be an important element of raised bog formation in drier regions (Glaser et al. 1997).

The hydraulic conductivity of catotelmic peat is generally very low, and flow through the catotelm only represents about 1% of discharge from the bog; most excess water flows laterally through the acrotelm (Damman 1986). The low permeability of the catotelmic peat results in rapid runoff during heavy rain events; runoff increases as the acrotelm becomes saturated (Bragg 2002; Holden 2005). The domed form of a raised bog causes all of this surplus water to pass through the rand and lagg, meaning that the lagg receives the largest amounts of water (Damman and Dowhan 1981). Because of the continuous saturation of the catotelmic portion of the peat mass, it is often assumed that there is water seeping out of the bog year-round to maintain baseflow in watercourses downstream (Bragg 2002). However, there are instances during dry weather when water is retained within the lagg, or indeed when water is retained within the peat mass and does not reach the lagg at all (Bragg 2002). Minor drainage features on the bog surface can dry up quickly in the absence of precipitation (Holden 2005), and the lagg stream may become stagnant or even dry out (Hebda et al. 2000). The annual water table fluctuations are usually larger at the bog margin, and consequently the peat in the lagg is more aerated (both spatially and temporally) compared to that in the bog center (Økland et al. 2001). Low summer flows and high winter runoff create growing conditions that restrict the vegetation in the lagg to species that are adapted to a fluctuating water table and a range of nutrient conditions (e.g., *Spiraea*, *Malus*, *Betula*).

Baird et al. (2008) observed that the peat at the margins of a raised bog had a significantly lower hydraulic conductivity than peat in the bog center, suggesting that the marginal peat may assist in retaining water in central bog areas, and that this low hydraulic conductivity at the margin might allow the bog to grow higher than if the marginal peat was more permeable. A lower hydraulic conductivity in the lagg could indicate that the lagg peat is more similar to catotelmic peat than the more porous acrotelmic peat. However, Levrel et al. (2009) present soil and peat profiles from eastern Canada showing that acrotelm and catotelm layers are present in the lagg, but that each layer is thinner than its counterpart in the adjacent bog. In addition, the von Post values (von Post 1924) in the peat profiles transitioned relatively sharply with depth in the lagg, changing from H1–H2 to H5–H6 over a 15 cm depth, whereas they varied more gradually with depth from H1 to H7 in the bog proper (Levrel et al. 2009).

Influence of Adjacent Land Use

While raised bogs are fed only by rainwater (and in some cases periodically supported by groundwater upwelling), the lagg is dependent on water from both the raised bog and the surrounding lands. Thus, if land use changes occur in the surrounding catchment, the lagg zone may be more sensitive to subsequent hydrological changes than the bog itself, which may partially account for the loss of most lagg zones in developed areas (Schouten 2002). The relative independence of a bog from regional ground water is only in the short to medium term. If regional ground water levels become low enough, the water mound in the bog will drop, followed by compaction and shrinkage of the peat (Schouten 2002).

The lagg plays a role in buffering the bog from the influence of mineral-rich waters (Hebda et al. 2000). Once a bog develops an ombrotrophic center, the influence of mineral soil water is restricted to the lagg zone (Damman 1986). However, it may not be possible for the lagg to adequately respond to anthropogenic changes in land use in the upland areas surrounding the bog, and the buffering capacity may be diminished or lost due to increased runoff entering the lagg zone from the surrounding areas. Once mineral-rich water enters a peatland, the water chemistry changes rapidly and impacts vegetation, peat chemistry, and rate of decomposition (Damman and French 1987). Evidence of such changes has been observed in Burns Bog, where mineral-rich runoff from surrounding industrial lands altered the vegetation in a perimeter bog ditch from historic lagg species (e.g., *Spiraea, Sphagnum*) to a near monoculture of invasive reed canarygrass (*Phalaris arundinacea*) (Dr. Richard Hebda, personal communication).

Lagg Indicators

The lack of lagg-specific research may be due in part to the difficulty of determining the actual location of the lagg of a raised bog. While there may be a clearly defined band of vegetation indicating the transition zone at the bog margin, there are many instances where the lagg is not obvious to the observer in the field. Being a transition between two different ecosystems and receiving runoff from both areas, the characteristics of a lagg are influenced by both the bog and the surrounding landscape. The mineral and nutrient quality of the minerotrophic sites surrounding bogs can vary widely, and thus the characteristics (e.g., chemistry, vegetation) of laggs can be equally variable. This variation creates challenges for defining specific hydrochemical or vegetation characteristics for laggs, even within a particular geographic region. Although the topographic depression of the lagg can be precisely located with high-resolution survey techniques (e.g., LiDAR, total station), these methods are not often available in the field. In the absence of such technology, there are a number of indicators that may assist in locating the lagg zone of a raised bog, benefitting not only field researchers but also those who may wish to define lagg boundaries for mapping or conservation purposes. In the following sections on chemistry and vegetation, we review the available literature on lagg-related research and discuss the utility of this information for lagg designation.

Chemistry

Ombrotrophic bogs are almost entirely fed by precipitation, resulting in a relatively uniform hydrochemistry within a particular region. In contrast, the hydrochemistry of the lagg zone is influenced by water from surrounding mineral soils and may vary widely within a region or even around a specific bog. Many researchers have proposed the use of chemical indicators to define the limit of influence of mineral soil water in ombrotrophic peatlands. Some of the most common measurements of the level of inflow of mineral soil water include pH, alkalinity, electrical conductivity, and calcium and bicarbonate concentrations in water (Bragazza and Gerdol 2002; Bourbonniere 2009). For example, calcium content can be ten times greater in mineral-influenced water than in bog water (Naucke et al. 1993; Hebda et al. 2000), where it is typically less than 2 mg/l (Tahvanainen 2004). A pore-water calcium concentration of 1 mg/l may be the lower limit for fen vegetation (Waughman 1980). Calcium is thus a useful indicator of the lagg transition. Other ions that have been found in higher concentrations in the lagg than the bog itself, and which may be useful indicators of the mineral soil water limit, include sodium, magnesium, aluminum, manganese, and silicon dioxide (Bragazza and Gerdol 1999; Tahvanainen et al. 2002; Bragazza et al. 2005).

The Ca:Mg ratio has been suggested as another indicator of the mineral soil water limit. A ratio of less than 1 has often been used to indicate ombrotrophic conditions (Waughman 1980). The Ca:Mg ratio measured in the upper peat layers of an ombrotrophic bog is typically less than that of rain water, indicating that the major source of calcium to the site is precipitation (Shotyk 1996). If the measured ratio is higher than local rainwater, it is probable that the additional calcium is of minerotrophic origin (Weiss et al. 1997; Muller et al. 2006). Bragazza et al. (2005) found that the Ca:Mg ratio dropped sharply within a few meters of the minerotrophic margin, particularly where the slope of the rand was steepest.

A Ca:Mg ratio of 1 may point to the location of the ombrotrophic-minerotrophic divide in some bogs (Naucke et al. 1993). However, as mentioned earlier, the chemical composition of the lagg is influenced by runoff from the surrounding mineral uplands, which may produce a wide range of calcium and magnesium concentrations even at different locations around a single bog. The ratio is also influenced by the distance from the sea and precipitation volume (Waughman 1980). Glaser et al. (1990) and Proctor (2003) found a Ca:Mg ratio of less than 1 in some of the bogs they studied, whereas Vitt et al. (1995) observed a Ca:Mg ratio of 2.5 in a bog, compared to 1.2–1.8 in fen sites. Wells (1996) suggested a Ca:Mg ratio of 2.5 as the mineral soil water limit, while Bragazza and Gerdol (1999) recommended a limit of greater than 2. Clearly, these values are specific to the geographic regions of study, highlighting the importance of site specific research into lagg zones instead of assuming universal ion concentrations. A general Ca:Mg ratio cannot be used to identify the mineral soil water limit unless a broad assemblage of these values has been measured for a representative number of bogs in the region of interest, and the average chemical composition of rainwater is known (Shotyk 1996).

Another well-established measure used to differentiate between bogs and fens is pH (Tahvanainen 2004; Sjörs and Gunnarsson 2002; Vitt et al. 1995). Calcium may correlate with pH across the lagg transition, and it is common for both indicators to be used when surveying the poor-rich gradient (Tahvanainen 2004). For example, Balfour and Banack (2000) used these two key indicators to define three broad water types for Burns Bog. Type I (pH: 3.5–5.5; Ca: 0–3 mg/l) was defined as “bog water,” correlating closely with typical bog plant communities and the extent of the water mound. Type II (pH: 4.5–6.0; Ca 3–10 mg/l) was "transitional water" surrounding the bog water but remaining within the peat mass. The presence of this transitional water type, and vegetative indicators, were used to delineate the locations of remnant lagg areas (Hebda et al. 2000). Type III water (pH: 5.0–8.0; Ca: >10 mg/l) was found outside the peat deposit and thus defined "non-bog water." This minerotrophic water type was rich in dissolved anions and cations, contained high concentrations of ammonia, iron, and manganese, and had a high electrical conductivity (Hebda et al. 2000). Glaser (1992) reported similar values for the bog–rich fen gradient in Minnesota peatlands: bog/poor fen, pH 3.7–4.6 and Ca 0.6–5.5 mg/l; weakly minerotrophic fen, pH 4.1–5.9 and Ca 0.9–13 mg/l; transitional rich fen, pH 5.9–6.8 and Ca 10–32 mg/l. A number of researchers have reported a bimodal distribution in the pH of peatlands, with bog pH below 4.5–5.0 and fen pH above 5.5–6.0 (Wheeler and Proctor 2000; Bourbonniere 2009), although a bimodal distribution is not found in all cases (e.g., Økland et al. 2001).

Blackwell (1992) used electrical conductivity (EC) as an indicator of the origin of water in the lagg zone of an Irish bog. Bog water is low in solutes, and thus has a very low EC. As ion concentrations increase toward the margin of the bog, so does the EC (Rydin and Jeglum 2006). EC measurements across the lagg zone therefore may indicate where the low conductivity water from the bog meets the water from the surrounding minerotrophic lands. Blackwell (1992) found that EC increased with depth and with proximity to a ditch at the bog border. Bubier (1991) similarly found that specific conductance increased significantly in the transition from open bog to rand forest and lagg.

Mitchell et al. (2008) found "hotspots" of Methylmercury (MeHg) in the upland/peatland interface of bogs in Ontario and Minnesota, particularly within 5 m of the upland interface. MeHg was higher in the lagg than in either the upland or peatland, suggesting that these hotspots are a result of net MeHg production within the lagg itself, rather than transport into the lagg from either the upland or the bog, although they do allow for the possibility of accumulation of MeHg-rich runoff in the lagg zone in addition to in situ production. In a related study, Richardson et al. (2010) observed elevated concentrations of sulfate, pH, total mercury, and MeHg in lagg areas (determined using LiDAR data) of forested wetlands.

Despite the value of the above parameters for assisting field researchers in determining the location of the lagg and the mineral soil water limit, it should be noted that the bog-lagg transition is a continuous gradient with considerable overlap between fen and bog types that does not display discrete boundaries (Sjörs and Gunnarsson 2002; Bourbonniere 2009). Wheeler and Proctor (2000) have even suggested abandoning the mineral soil water limit as a useful boundary between ombrotrophic and minerotrophic sites, due to inconsistencies in the correlation of vegetation and water chemistry. On the other hand, Økland et al. (2001) argue that the mineral soil water limit is hydrologically distinct and "characterized by at least a local set of indicator species" and suggest that it remains a useful concept. We concur with Økland et al. (2001) that the mineral soil water limit is useful and may be a key element in locating the lagg within the mire margin–mire expanse gradient. However, it should be stressed that the hydrochemical gradients causing vegetation changes across this transition zone are site specific, only locally valid (Wheeler and Proctor 2000; Bragazza et al. 2005), and change seasonally (Fig. 1).

Vegetation

Dense tree and shrub layers tend to be associated with the lagg (Rydin et al. 1999), with sedges and herbaceous species making up the understory (Hebda et al. 2000). Peat is relatively shallow in the lagg (e.g., <0.5 m), allowing deeply rooted vascular plants to make contact with the underlying mineral soil (Gorham 1950; Rydin et al. 1999). Surface water in the lagg generally flows faster than in the bog, and therefore is more aerated than the often stagnant bog water, enabling growth of plant species that are not tolerant of bog conditions, for example, those that lack aerenchyma or depend on mycorrhiza (Rydin et al. 1999). Since trees and larger shrubs are able to colonize the lagg zone, productivity is much higher in the lagg than the center of a raised bog. Damman (1979) reports that nutrient-poor fen vegetation in a lagg is 10–20 times more productive than vegetation in the bog center. Despite a higher productivity in the lagg, the lack of aeration and lower pH in the bog center results in a much-reduced rate of decomposition and faster peat accumulation in the bog center than in the lagg.

The plant species composition of the lagg is strongly influenced by the amount, level, fluctuation, and chemical quality of the water from the bog and surrounding lands (Ivanov 1981), in other words, the depth to water table and the pore-water/peat chemistry (Hájková and Hájek 2004; Bragazza et al. 2005). The variation of these environmental gradients across the "mire margin–mire expanse" transition will affect not only species composition, but also the distribution and vegetational patterns (Jeglum 1971). Hydrochemical changes are evidenced by both plant species composition and physiognomic variations within species (Damman 1986). When it is not possible to conduct detailed field observations on the hydrological and hydrochemical properties of the lagg transition, it may be possible to use vegetational changes as an indicator of these lagg characteristics (Howie et al. 2009a).

Since runoff from bogs will tend to be similar to rainwater, it is the mineralogy of the parent materials surrounding the bog that will, in part, determine the variability of lagg species around the bog perimeter (Damman and French 1987). The origin and thus hydrochemistry of these waters is dependent on the types of mineral deposits they have passed through and the amount of time spent in each soil type (Schouten 2002). The soil and vegetation of the surrounding landscape are usually not uniform around a raised bog, resulting in variable species composition at different locations within the lagg. For example, Damman and Dowhan (1981) observed that most of the lagg surrounding a bog in Nova Scotia consisted of an extremely nutrient-poor fen, but one section of the lagg was characterized by a richer fen as a result of a stronger influence by minerotrophic waters.

Some researchers have suggested that one can use fen species as an indicator of the mineral soil water limit (e.g., Rydin et al. 1999). This idea is based on the premise that most species are not tolerant of ombrotrophic conditions, and thus would only be present if the mineral/nutrient conditions were able to support species not typical to a bog environment. However, there are a number of reasons, other than the presence of the lagg zone, that fen or swamp species may be present in a bog. For example, some bogs may be young or very slow in developing, such that the depth of peat is less than the rooting zone of some species, allowing non-bog species to survive in what is technically an ombrotrophic environment (Glaser et al. 1990). In other instances, mineral soaks or flushes may appear in the center of a bog (Schouten 2002) and not be related to the perimeter lagg zone. One must also keep in mind the geographic variation in species distribution; a genus that is only found in fens in one part of the world may be tolerant of bog conditions in another region. In order to identify fen indicator species for a particular site, one must be aware of the response of plant species to the abiotic conditions specific to that site (Bragazza et al. 2005). If the distribution of particular species can be correlated to other parameters across the lagg transition, such as pH or calcium concentrations, it may be acceptable to consider these as indicators of the mineral soil water limit or lagg transition.

Tree Height and Density

A raised bog is often open in the center with scattered, dwarfed coniferous trees, while the lower rand may support a marginal forest (Rydin et al. 1999). Tree growth in peatland margins is related to increased nutrient availability, a lower water table resulting in peat aeration, and peat decomposition (Bubier 1991; Bragazza et al. 2005). The high water table limits tree development in the bog center (Freléchoux et al. 2004). The greater slope, more rapid drainage, and steeper hydraulic gradient result in a lower water table below the rand of a raised bog (Ingram 1983). As the water table drops through the rand and nutrient concentrations increase in the bog margin, the typical vegetation response is an increase in tree height and density (Malmer 1986). Howie et al. (2009a) studied historic air photos of Burns Bog and determined that tree height increased through the rand. Freléchoux et al. (2004) found similar results, where pine trees at the margin of a bog in Switzerland grew on average three times faster than those in the wettest study plots (where there were also numerous dead pines). Bubier (1991) similarly found a significant increase (approximately double) in tree height in the rand adjacent to a lagg stream. Drainage of a peat bog can exacerbate this effect, improve growth and allow trees to invade and establish further toward the center of a bog (Brooks and Stoneman 1997).

In terms of tree density, Freléchoux et al. (2000) observed a low density of small pine trees in the central, wetter parts of bogs, compared to a higher density of taller pines in the drier rand of the bog. Bubier (1991) found similar results for *Picea mariana* (black spruce) for a raised bog in Vermont. However, this trend in tree density can be less clear in the presence of another tree species; Freléchoux et al. (2004) looked at the pine-spruce interface and found that pine density decreased as spruce density increased towards the bog margin. Once trees have become established in the rand, they further enhance conditions for their own growth through increased evapotranspiration and nutrient additions via leaf litter (Damman and Dowhan 1981), leading to higher rates of seedling establishment and subsequently greater stand density.

Tree growth increases in the rand (Damman and French 1987), and can be used to indicate the general region of transition from bog to lagg. The presence of tall and dense trees may indicate the lower rand or the zone immediately adjacent to the lagg rather than the lagg. The lagg itself tends to be an area where water collects as it leaves the bog. For example, Keough and Pippen (1984) observed that the lagg zone displayed high water following rain, and Malmer (1986) showed that water level fluctuations are more extreme at the bog margin where the water table rises quickly after rain and drops quickly during drought. Due to the relatively high and fluctuating water table, this zone is often associated with floating *Sphagnum* species (e.g., *S. cuspidatum*) (Keough and Pippen 1984), sedges, and shrubs (Hebda et al. 2000). However, there are also cases where water does not collect in a topographic depression between bog and upland, but rather diffuses gradually across relatively flat land (Fig. 1; Howie et al. 2009a). In these situations, the water table may be lower and larger trees (e.g., swamp forest) may dominate the lagg vegetation (Hebda and Biggs 1981; Hebda et al. 2000).

The Role of the Lagg in Raised Bog Restoration

Raised bogs have been heavily impacted by peat mining, agriculture, and drainage worldwide. Bogs that have been mined and/or drained do not usually regenerate to proper functioning condition without intervention (Price et al. 2003) due to increased evapotranspiration, dry surface conditions, crust formation, peat compression, and forest encroachment. The two main bog restoration techniques currently used are rewetting and revegetation (Price et al. 2003). Rewetting can be achieved by ditch blocking, construction of "bunds" or dykes around the peat mass, or digging lagoons to raise the water table locally (Wheeler and Shaw 1995). Rewetting is generally a pre-requisite for revegetation. Natural recolonization may be supplemented by transplanting from suitable donor sites, seeding with local stock, or broadcasting diaspores of *Sphagnum* and other bog species. Tree removal may assist in the establishment of desired plant species (e.g., *Sphagnum*) by removing a significant source of evapotranspiration, leaf litter, and shade. Two examples of current restoration projects include Burns Bog in western Canada (Howie et al. 2009b), and the Bois-des-Bel peatland in eastern Canada (Andersen et al. 2010).

Increased drainage as a result of peat mining or agriculture may have long-term impacts on the water balance of a bog. Drainage of the lagg leads to increased runoff from the bog and less storage in the bog (Blackwell 1992). Thus, drainage management at the border of the bog and beyond may be important to protecting the hydrological function of the adjacent raised bog (Wheeler and Shaw 1995; Ginzler 1997). In terms of hydrological restoration of a raised bog, the lagg must perform two key functions: i) sustain the dome of water in the peat body by maintaining a high water level in the lagg and, ii) allow for excess water to leave the bog during times of high precipitation and runoff.

It has been recommended by a number of researchers that a buffer zone be included in any raised bog conservation area. Burlton (1997) includes the "catchment" that feeds the lagg system from outside the bog as an important element in conservation because the water level in surrounding lands impacts the water level in the lagg zone, which in turn influences the hydrology of the bog. Schouwenaars (1995) used the term "hydrological buffer zone" to recommend retaining a high water level in the lagg, thereby reducing the hydraulic gradient and promoting a higher water table in the bog itself.

Encouragingly, some discussion of lagg restoration has appeared in recent western European literature. In reporting on the Dutch-Irish bog restoration collaborative of the 1990s, Schouten (2002) emphasized the importance of restoring the hydrological conditions of the lagg zone when attempting to restore Irish bogs. Brooks and Stoneman (1997) discuss the use of perimeter clay bunds around a raised bog in the re-creation of a lagg fen system, where mineral enrichment from the clay is acceptable at the bog border provided that the water table does not rise above the bog surface. Restoration of four lowland raised bogs in Cumbria, northwest England, included rewetting of the bog border and adjacent farmland to re-establish lagg conditions (Mawby and Brock 2007). The UK Joint Nature Conservation Committee has introduced the concept of "hydrological protection zones" for the lagg areas around raised bogs, where areas outside the peat body may be included in the conservation area such that the water table in these areas can be raised to support the water table in the bog (Morgan-Jones et al. 2005). The purpose of these hydrological protection zones is to maintain suitable hydrological conditions within the raised bog and to allow the occasional seasonal flooding that naturally occurs in a lagg zone. Sottocornola et al. (2009) recommend the conservation of peatland borders and nearby areas of an Irish blanket bog to increase the plant biodiversity of the bog conservation area.

In North America, relatively little emphasis has been placed on lagg restoration to date. Most bog restoration research projects focus on restoring *Sphagnum* cover to remnant or cut-over sections of peatlands, rather than attempting to restore the function of the complete raised bog system. In 2006, an interdisciplinary technical workshop with invited government and academic experts was held in Vancouver, British Columbia to discuss lagg concepts in relation to the restoration of Burns Bog. The key message from the workshop was that it is important to restore the lagg at the same time as the bog is restored. It was noted that a high water table in the lagg will and must support the raising of the water table in the bog proper. The title of the document resulting from the workshop was "A Lagg is not a Ditch" (Peart 2006). This referred to the perimeter ditches that surround Burns Bog (and other bogs) and inferred that they do not function like a natural lagg, in terms of hydrology, hydrochemistry, and ecology. The central question, in this case, is whether a functional lagg can be artificially created for a degraded raised bog. Research focused on lagg characteristics and function (including hydrology, hydrochemistry, vegetation, and geomorphology) is necessary to answer these types of questions for restoration of damaged lagg zones, and correspondingly, for the restoration of the bog with which the lagg is associated.

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